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Potential fire behavior in pine flatwood forests following three different fuel reduction techniques

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Abstract

A computer modeling study to determine the potential fire behavior in pine flatwood forests following three fuel hazard reduction treatments: herbicide, prescribed fire and thinning was conducted in Florida following the 1998 wildfire season. Prescribed fire provided immediate protection but this protection quickly disappeared as the rough recovered. Thinning had a similar effect on fireline intensity. Herbicides produced a dramatic decrease in fireline intensity from year 2 to 6 but had little effect on fire severity, thus increasing the likehood of root kill resulting in tree death if wildfire occurs during drought conditions. Treatment combinations, such as thinning and herbicide may provide immediate and long-term fireline intensity reductions as long as forest managers take into account each alternative's strengths and weaknesses. Published by Elsevier Science B.V.

Keywords: Fuel model; Herbicide; Prescribed fire; Mechanical thinning; Wildfire intensity

1. Introduction

In 1998, Florida experienced one of the worst fire seasons in its history (Karels, 1998). From mid-May to mid-July, >2000 wildfires burned >200,000 ha of forest and in central and northern Florida. Most were high-intensity/high-severity, stand-replacing fires that required 10,000+ firefighters from 49 states to suppress them and destroyed or damaged 370 businesses and residences. Commercial timber losses in excess of US$ 350 million, suppression costs in excess of US$ 100 million and estimated tourism losses of nearly US$ 140 million all contributed to the total estimated cost of US$ 622–880 million (Mercer et al., 2000). The magnitude and severity of the wildfires prompted several land management agencies, including the USDA Forest Service and the USDI Biological Resources Division, to combine resources and study the ecological and economic impacts of the Florida wildfires. Among their joint studies was this one on ways to reduce hazardous fuels in commercial pine stands and at the urban/wildland interface.

Dormant-season low-intensity prescription fire every 4-5 years has been the practice of choice to control the buildup of highly flammable understory vegetation (the rough) throughout the southern United States (Pyne et al., 1996). Frequent reburning of the rough is necessary because it rapidly redevelops, bringing the fire hazard to its preburn level in <5 years (Davis and Cooper, 1963). In the recent decades, however, this practice has been constrained by smoke management, liability issues and public concerns

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about the ecological ramifications of fire (Wade, 1993).

The continuing need for hazardous fuel reduction and the social limitations of prescription fire have prompted interest in developing other strategies for managing hazardous fuels. Two potential treatments are thinning and herbicide. Thinning and deferred shelterwood harvests are used by public land management agencies charged with meeting widely diverse resource goals while maintaining a continuous forest cover (Smith, 1996). Herbicides are used as a mid-rotation treatment in commercial pine plantations to boost growth and reduce future site preparation costs (Oppenheimer et al., 1989). Both treatments reduce height, percent cover and/or loading of the highly flammable rough although the degree and longevity of hazardous fuel control has not yet been well defined.

Fuel and computer models are available to test the ability of different fuel reduction techniques for modifying fire behavior. For example, Hough and Albini (1978) developed detailed fuel models and fireline intensity prediction tables for southern forest managers to estimate fire behavior for a variety of stand conditions by gathering appropriate data about understory fuels. Stephens (1998) used FARSITE (Finney, 1996), a GIS-based fire prediction system to evaluate silvicultural treatment effects on fire behavior and tree mortality for a watershed in Yosemite National Park. BEHAVE, another fire prediction system, consists of two subsystems, five programs and 13 modules (Burgan and Rothermel, 1984; Andrews, 1986; Andrews and Chase, 1989). It applies existing fuel models (Anderson, 1982) or custom-designed ones to predict the behavior of head fires for a given set of environmental conditions.

The objective of this study was to compare the potential fire behavior in pine flatwood forests after treatment with one of three silvicultural techniques at five different ages-of-rough. The study was two-phased, a detailed inventory of understory fuels followed by computer simulations. We chose the BEHAVE system to create custom fuel models and simulate flame length and rate of spread for each treatment/rough age combination. To match the drought conditions of the 1998 wildfires, fire behavior was simulated for each treatment/rough-age combination under drought as well as normal weather conditions. The advantages and disadvantages of each technique from a resource protection and fire danger perspective are discussed based on comparing fire behavior outputs to existing suppression difficulty charts. If practical alternatives to prescribed fire for reducing hazardous fuels can be found, resource managers will have a wider choice of methods to reduce the risk of damaging wildfires in commercial pine stands and at the urban interface, in the southern United States and elsewhere.

2. Materials and methods

2.1. Study sites

Fuels data collection for this study took place during winter 1998-I 999 at three sites located in the Coastal Plain Physiographic Province of northern Florida. Site 1 was north of Olustee on the Osceola National Forest in Baker and Columbia counties (30°30′N, 82°30′W). Site 2 was on forest industry (Georgia-Pacific and ITT Rayonier) land located between Lake Butler and Starke in Bradford and Union counties (30°15′N, 82°15′W). Site 3 was on land owned by the St. Johns River Water Management District and the Florida Division of Forestry, located between Lake George and Daytona Beach in Putnam and Volusia counties (29" 15′N, 8 1 °15′W).

The study sites consisted of nearly flat terrain intermixed with slight depressions at elevations of 25–50 m above mean sea level. Mean annual precipitation for these sites is 140 cm, with half occurring between May and August and the remainder distributed fairly evenly throughout the other months. Mean annual temperature for the study sites is 19 °C with a January mean minimum of 5 °C and an August mean maximum of 33 “C. The average growing season is 286 days (Baldwin et al., 1980; Watts, 1996).

The three study sites were within the North Florida flatwoods ecological community and dominated by longleaf pine (*Pinus palustris*) and/or slash pine (*P. elliottii var elliottii)* in the canopy (Table 1). Depending on soil drainage and past land use history, some sites were slash pine plantations and others were naturally regenerated mixtures of slash and longleaf pines. Gaillberry (Ilex glabra) and/or saw palmetto (Serenoa repens) dominated the understory. However,

Table 1
Characteristics (min-max) of the dominant vegetation on the untreated areas at the study sites (three stands per site)

Characteristic	Sites		
	Thinning	Prescribed fire	Herbicide
Tree species	Slash pine	Slash and longleaf pine	Slash pine
Tree age (years)	31–40	85–90	17
Stand origin	Planted	Natural	Planted
Basal area (m^2/ha)	25-30	15-20	25-30
Tree height (m)	22-25	19-22	IO-14
Tree diameter (cm)	40-50	45-55	20-25
Galiberry cover (%)	45-65	17–27	70-75
Saw palmetto cover (%)	35–45	60-75	5–10

the understory also included other shrubs, various grasses, hardwoods and vines.

General soil characteristics were rather uniform among and within the three study sites. All soils were of the Mascotte, Myakka, Pelham, Pomona and Sapelo series, which are deep somewhat poorly drained fine sands formed from thick deposits of sandy and loamy marine deposits (Baldwin et al., 1980; Howell, 1984; Dearstyne et al., 1991; Watts, 1996). According to land management records, site index varied considerably among and within the study sites. At the Osceola NF, site index for longleaf pine at age 50 ranged from 21 to 23 m compared to 26 to 30 m on the St. Johns site and 18 to 21 m for slash pine at age 25 on industry land.

2.2. Study design

Because of varying management objectives, each site represented a different silvicultural practice with prescribed fire at the Osceola NF, herbicide on forest industry land and thinning on St. Johns land. This paper identifies sites by their silvicultural practice. The prescribed fire treatment was a dormant-season burn on a 3-5 year rotation with low to moderate intensity and no mortality to canopy dominants. The herbicide treatment was Garlon 4 applied mid-rotation in autumn by a skidder-pulled mistblower at a rate of 5.01/ha. The thinning treatment was a commercial thin-harvest operation that left 12-20 m^2/ha of basal area.

At each site, 15 stands varying from 4 to 35 ha in size were chosen based on the age of rough which is the number of years (1, 2, 3, 5, or untreated) since the last application of the silvicultural practice. The untreated age class consisted of stands with no silvicultural treatment since planting and included some that had been unmanaged for up to 40 years. The 5-year-old class consisted of 4-year-old rough at the prescribed fire site, 5-year-old rough at the thinning site and 6-year-old rough at the herbicide site. All sites had three or more stands in each of the five age classes. Combining these five age classes with the three silvicultural treatments created a 3 x 5 factorial with three replications.

For the most part, treatments were exclusive from one another. One exception was at the thinning site where a few stands had received some low-intensity, dormant-season prescribed fires either immediately before or after logging. The effects of these fires were judged minimal relative to the impact of the thinning. Also, several stands at the herbicide site had undergone a commercial thinning that removed about 50% of the basal area and reduced and disrupted the rough 2 years earlier. Three of these were selected and included in the study as a fourth treatment within the rough age 3 category.

2.3. Fuel model develonment

In each stand, understory fuel characteristics (cover, height and loading by size class) were collected as inputs to BEHAVE to build custom fuel models. To determine percent cover and height, six 65 m-long transects were systematically located 25 m apart and parallel to one another near the center of each stand. The vegetation was sampled along each transect at 5 m intervals by holding a 2.5 m tall range pole perpendicular to the ground and recording each plant species touching the range pole and the height of the tallest plant. Percent cover and height to the nearest 0.1 m were determined for five categories; grass, open space, saw palmetto, small shrub and tall shrub. Grass included all graminoid species, *Andropogon* spp., *Aristata* spp., and *Panicum* spp. Tall shrub was primarily gailberry but also included all other woody shrubs $\geq$0.3 m tall while small shrub included all <0.3 m tall, e.g. blueberry (*Vaccinium* spp.) and runner oak *(Quercus pumila)*. Open space represented areas devoid of vegetation but usually blanketed by pine litter. Because sampling took place in January and February, no forbs were found.

At every fifth sampling point, basal area was measured using a IO-factor prism. The nearest dominant or codominant tree was identified to species and measured for DBH (diameter at 1.37 m) and total height.

Measurements of saw palmetto cover and overstory basal area were applied to existing equations to estimate fuel loadings for the thinning and prescribed fire treatments (MCNab et al., 1978). In all herbicide-treated stands, the clip-bag-dry method was used because the equations were unsuitable for this treatment. In four of the thinning- and prescribed fire-treated stands this method was also used to verify the accuracy of the equations. In the clip-bag-dry method, six 1.0 m^2 quadrats were located on a 30m x 30 m grid near the center of the stand. Quadrats were delineated by a 1.0 m x 1 .O m sampling frame and all vegetation, living and dead, within the frame and between 0.1 and 3.0 m tall was designated as grass or shrub fuels before being clipped

Table 2
Key characteristics[a] of the custom fuel models for the herbicide, prescribed tire thinning and thin-herbicide treatments in untreated and rough age 1–5 years

Treatment / Age-of-rough (years)	Fuel loading[b] 1 h (Mg/ha)	10 h (Mg/ha)	Live woody (Mg/ha)	Height (m)	Surface-to-volume ratio (cm^2/cm^3)	Moisture of extinction (%)
Herbicide						
Untreated	21.24	5.69	6.63	0.69	2116	35
	19.15	4.61	0.18	0.52	2100	34
	18.77	2.80	0.13	0.13	1896	40
	17.65	1.61	0.07	0.06	1816	41
	11.92	2.20	0.81	0.10	1883	32
Prescribed fire						
Untreated	2X.58	7.15	8.78	0.67	2112	41
	3.07	0.29	1.05	0.12	2161	27
	9.34	0.81	2.69	0.31	2097	28
	14.00	1.23	4.23	0.42	2108	31
	17.45	1.79	4.59	0.43	2069	34
Thinning						
Untreated[c]	33.47	14.45	12.90	0.78	2171	42
	9.79	0.36	4.08	0.22	2188	34
2	18.39	1.39	6.94	0.32	2162	33
	15.34	3.58	6.36	0.58	2205	32
5	19.17	3.65	9.07	0.81	2238	33
Thin/herbicide						
	12.43	1.61	0.40	0.10	1899	30

[a] Other key characteristics, live woody S/V ratio (2314) and heat content (3996 kJ/kg), were averages from Hough and Albini (1978) and kept the same for all fuel models.

[b] Live herbaceous fuel load was 0.05 Mg/ha for all fuel models except TUH-3 which was 0.77 Mg/ha. No 100 h fuels were included in any of the fuel models because of their scarcity.

[c] Stand with a rough age >10 years.

and bagged. All plant material on or in the forest floor (O_i and 0, horizons) was likewise collected and designated as litter fuel.

Fuel samples were dried at 90 °C to a constant weight in a wood-drying oven, separated by type (grasses, pine litter including dead downed woody material and shrubs) and sorted into the diameter classes (<0.63 and 0.63–2.54 cm) that correspond to the 1 and 10 h time-lag fuel classes (Fosberg, 1970). Fuels >2.54 cm were virtually nonexistent and ignored for the purposes of this study. After separation, fuels were weighed to the nearest 0.1 g on an electronic scale.

The fuels data from both inventory methods were entered into the NEWMDL program (Burgan and Rothermel, 1984) of BEHAVE to create a custom fuel model (Table 2) for each treatment/age-of-rough combination. Physical and chemical characteristics of gallberry-palmetto fuel complex for the custom fuel models were obtained from Hough and Albini (1978).

2.4. Fire simulations

The Osceola National Forest provided average monthly weather data-including cloud cover, ambient air temperature, relative humidity, 6-m windspeed, precipitation and fuel moistures for-June 1997, considered normal based on the mean monthly precipitation and temperature record for the past 105 years in north-central Florida (NOAA, 2000) and for the June 1998 drought (Table 3). Fuel models developed for this study were combined with this weather data and pertinent landform data in the SITE module of the FIRE1 program to calculate specific fire behavior estimates for each treatment/age-of-rough combination (Andrews, 1986). Each simulation was of a summer fire (15 June) burning under normal and drought weather conditions. Outputs were the predicted flame length (m) and rate of spread (m/min) of a head fire. A few of the outputs were compared to estimates derived from existing fire behavior prediction tables for the galliberry, palmetto fuel complex (Hough and Albini, 1978) as a quality check.

Predicted fire behavior outputs from each simulation were compared to fire characteristic, suppression charts (Andrews and Rothermel, 1982) to rate the difficulty of controlling a wildfire burning under drought and normal conditions.

Table 3
Drought normal weather and environmental conditions used in the tire simulations

Characteristic	Drought	Normal
Drought index (KBDI[a])	731	293
Ambient air temperature (‘C)	36	29
Relative humidity (%)	42	65
Windspeed (km/h)	11.3	1.7
Cloud cover (%)	10	40
1 h fuel moisture (%)	5	15
10 h fuel moisture (%)	6	13
Live woody fuel moisture (%)	104	166
Days w/o rain	25	15
30-day rainfall total (cm)	5.4	13.2
Slope (%)	0	0
Elevation above sea level (m)	33	33
Latitude	30°N	30°N

[a] Keetch–Byram Drought Index assesses the combined effect of evapotranspiration and amount of precipitation in producing moisture deficits in the soil (Keetch and Byram, 1968). It was developed specifically for fire potential assessment in southern USA and provides a scale from 0 to 800 with 800 representing desert-like conditions.

2.5. Statistical analysis

Analysis of variance with Student-Newman-Kuels mean separation test was used to compare treatment differences for cover, height and loading of fuel types and sizes among and within the different ages-of-rough (SAS, 1993). In all tests $\alpha = 0.05$ and data were transformed as needed to correct for unequal variances and non-normality of residual values.

3. Results

3.1. Fuelbed characteristics

Generally, percent cover of the different species groups varied little in the thinning and prescribed fire treatments (Table 4). Gallberry and saw palmetto dominated untreated stands at both locations. Percent cover of these species decreased slightly in the first year but quickly recovered. Grass, open space and small shrub cover were absent-to-scarce in these stands before treatment and showed only modest gains in coverage for a couple of years after treatment before decreasing again. Gallberry dominated the herbicide treatment stands before spraying but afterwards was

Table 4
Cover (mean percent ± 1 S.E.) of grass, litter and shrubs by treatment and age-of-rough

Treatment	Age of rough (years)				
Fuel type	Untreated[a]	1	2	3	5
Herbicide					
Grass	0 ± 0 C[b]a[c]	0.9 ± 0.4 Cc	6.7 ± 0.9 Aa	4.9 ± 0.4 Bc	0.9 ± 0.2 Ch
Litter	18.7 ± 0 1.7 Ca	20.0 ± 2.0 Ca	34.2 ± 1.8 Ba	69.8 ± 4.8 Aa	69.3 ± 4.2 Aa
Saw palmetto	6.7 ± 0.8 Cc	3.1 ± 0.2 Db	9.3 ± 0.2 Bc	0.2 ± 0.2 Ec	19.6 ± 0.3 Ab
Short shrub	1.8 ± 2.1 Ah	0.4“ ± 0.6 Ac	0.2’ ± 0.1 Ab	0.1 ± 0.1 Ab	0.2 ± 0.2 Ab
Tall shrub	72.9 ± 7.5 Aa	75.6’ ± 7.0 Aa	49.8’ ± 5.3 Ba	25.3’ ± 3.2 Cb	10.2 ± 0.8 Db
Prescribed fire					
Grass	0 ± 0 Da	14.7 ± 1.7 Aa	7.6 ± 0.5 Ba	10.2 ± 1.4 Bb	3.6 ± 0.6 Ca
Litter	6.2 ± 1.7 Bb	17.8 ± 2.0 Aa	4.0 ± 0.8 Cc	0.9 ± 0.2 Dd	6.7 ± 1.2 Bc
Saw palmetto	67.1 ± 5.8 Aa	33.8 ± 3.2 Ba	53.8 ± 5.2 Aa	56.4 ± 4.9 Aa	56.0 ± 5.3 Aa
Short shrub	4.4 ± 1.1 Da	15.6 ± 1.6 Aa	6.2 ± 0.8 Ca	7.1 ± 1.2 Ca	11.1 ± 1.2 Ba
Tall shrub	22.3 ± 1.8 Bc	18.1 ± 1.0 Cb	28.4 ± 2.3 Ab	25.4 ± 2.2 ABb	22.6 ± 2.3 Ba
Thinning					
Grass	0 ± 0 Ba	9.8 ± 3.4 Ab	11.8 ± 3.5 Aa	6.3 ± 2.4 Ac	0 ± 0 Bc
Litter	3.7 ± 1.7 Bb	18.7 ± 3.1 Aa	14.2 ± 2.8 Ab	12.7 ± 1.8 Ac	18.6 ± 3.2 Ab
Saw palmetto	40.7 ± 5.8 ABb	36.9 ± 5.2 Ba	34.7 ± 6.2 Bb	31.6 ± 4.9 BCb	55.6 ± 8.3 Aa
Short shrub	0.2 ± 0.1 Bb	9.3 ± 2.6 Ab	2.9 ± 1.3 Bb	2.7 ± 1.2 Bb	1.1 ± 1.2 BCb
Tall shrub	55.3 ± 5.5 Ab	25.5 ± 3.5 Cb	36.4 ± 4.3 Abb	46.6 ± 5.2 Aa	24.6 ± 3.3 Ca
Thinning/herbicide					
Grass	[d]		–	51.4 ± 4.7 Aa	
Litter		–	–	31.7 ± 2.8 Bb	
Saw palmetto		–	–	1.0 ± 0.9 BCc	–
Short shrub		–	–	I.0 ± 0.1 Bb	
Tail shrub				153.3 ± 3.2 cc	

[a] Untreated stands with a rough age >1 0 years.
[b] Means followed by different uppercase letters are significantly different within that treatment and fuel type (a = 0.05).
[c] Means followed by different lowercase letters are significantly different within that year and fuel type (α = 0.05).
[d] No data collected for this treatment at this time.
[e] Shrubs were dead but still standing during these years, alive in all other years.

replaced by open space covered with pine litter. The thinning-herbicide treatment produced substantial coverage by several grass species as well as considerable amount of open space covered with pine litter. Saw palmetto was lacking in all herbicide treatments because of intensive site preparation when the plantations were established.

In all treatments, the tallest shrubs were found in the untreated stands (Fig. 1). In the thinning and prescribed fire treatments, shrubs were shortest in the first year, but began to grow steadily in second year and were nearly as tall as the shrubs in the untreated stands by the fifth year. In the herbicide stands, height reduction was initially not significant as the dead shrubs remained standing for about 2 years. By the third year, the dead shrubs had fallen, creating rather open stands. Some shrub growth was detected in the fifth year but this was attributed to skips in the spraying that allowed them to survive. The few remaining shrubs in the thin-herbicide treatment were similar in height of shrubs in the herbicide stands at age 5.

In the prescribed fire and thinning treatments, fuel loadings were generally distributed according to shrub height data (Tables 4 and 5). The heaviest loadings were found in the untreated stands and were usually dominated by the 1 h fuels in the litter and shrub fuel types. Lightest loadings were found in the first year after treatment and the loading gradually increased with each subsequent year. Loadings in the herbicide

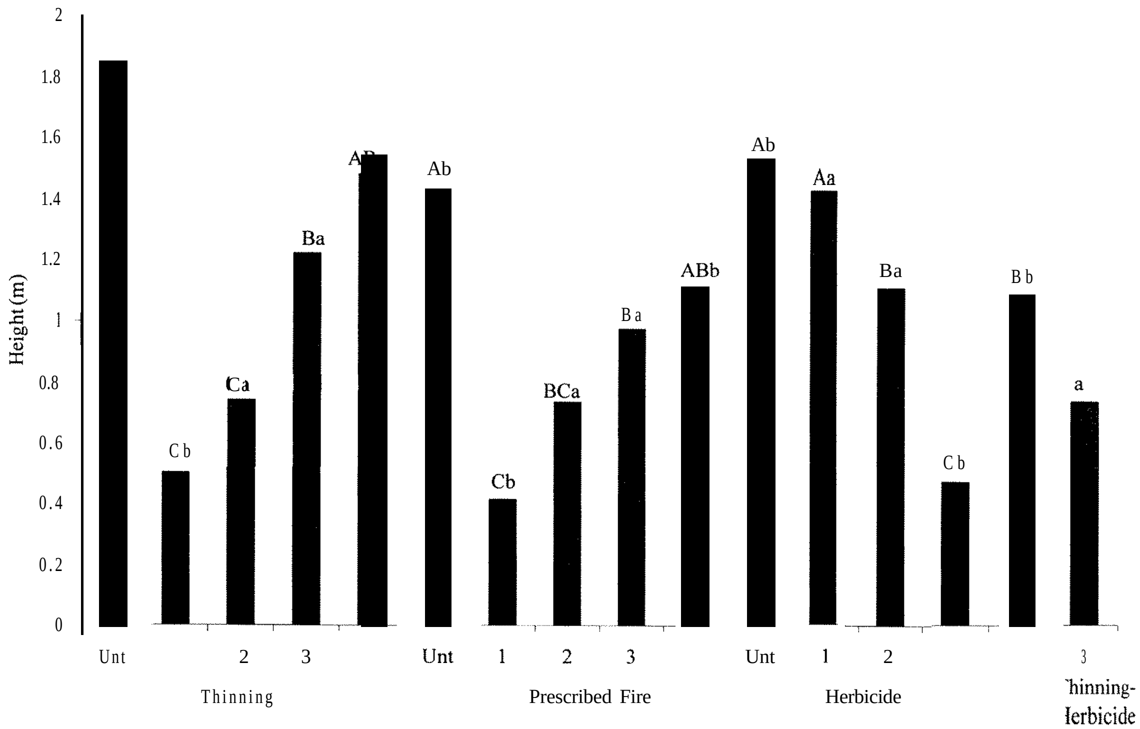

Fig. 1. Average height of grass or shrubs <0.1 m tall in untreated pine flatwood stands and in stands influenced by fuel reduction technique (herbicide, prescribed fire, thinning, or thinning-herbicide) and time in years (1, 2, 3 and 5) since last application of the practice. Bars with different uppercase letters are significantly different within that treatment while bars with different lowercase fetters are significantly different within that age-of-rough ($\alpha = 0.05$)

treatment decreased gradually through time and shifted from the shrub layer to the forest floor. Loadings of the different size classes and fuel types in the thinning-herbicide treatment were quite similar to the similarly aged herbicide-only treatment.

3.2. Flume length predictions

Predictions of flame length followed two distinct patterns in the treatments as the rough changed from untreated to recently treated (year 1) and then matured to year 5 (Fig. 2). Under drought conditions in the thinning and prescribed fire treatments, flame length predictions showed a U-shaped distribution. The longest flame lengths (5-7 m) were in the untreated simulations. Flame length dropped in the first year after treatment but increased steadily each year thereafter. By age 5, flame length was 5.5 m for thinning and 4.0 m for prescribed fire, 80 and 63% of their respective untreated simulations. Generally, normal weather reduced the drought flame lengths by about 30%, across all ages.

In the herbicide treatment, the flame length pattern as rough age increased resembled an inverse J (Fig. 2). Under drought conditions in the untreated stands, predicted flame length was 5.2 m and declined only slightly by age 1. However, at age 2 flame length plummeted to 2.4 m and continued downward to 0.4 m at age 3 before slightly rebounding to 1.0 m at age 5. Flame length estimates for normal weather conditions followed this pattern but were reduced by about 30% relative to drought.

The thinning-herbicide treatment (age 3 only) produced flame length estimates similar to the herbicide treatment at age 5 (Fig. 2). Under drought conditions, predicted flame length was 1 m. Normal

Table 5
Fuel loadings (mean Mg/ha ± 1 S.E.) of grass, litter and shrub fuels by treatment and age-of-rough

Treatment	Age of rough (years)				
Fuel type size	Untreated[a]	1	2	3	5
Herbicide					
Grass	0 ± 0 B[b] a[c]	0.1 ± 0.1 Bb	0.7 ± 0.2 Aa	0.2 ± 0.1 Ba	0.1 ± 0.1 Ba
Litter, 1-h	10.6 ± 0.4 cc	12.6 ± 0.6 Ba	16.8 ± 0.7 Aa	16.8 ± 0.8 Aa	11.1 ± 1.1 BCa
Litter, 10-h	1.3 ± 0.7 Ah	0.9 ± 0.3 Aa	2.1 ± 1.1 Aa	1.4 ± 1.1 Aa	1.7 ± 0.5 Aa
Shrub, 1-h	7.8 ± 0.6 Ab	7.8 ± 0.6 Aa	2.5 ± 0.3 Bc	0.6 ± 0.3 Cc	3.6 ± 0.5 Bc
Shrub. 10-h	4.5 ± 0.5 Aa	4.5 ± 0.5 Aa	1.4 ± 0.6 Ba	0.2 ± 0.2 cc	2.0 ± 0.6 Bb
Prescribed fire					
Grass	0 ± 0 Ca	1.2 ± 0.2 Aa	0.6 ± 0.3 Ba	0.7 ± 0.3 Ba	0.3 ± 0.2 BCa
Litter, 1-hr	25.2 ± 2.2 Aa	3.X ± 0.5 Cb	4.6 ± 0.4 Cb	9.0 ± 0.7 Bc	12.2 ± 2.1 Ba
Litter, 10-hr	2.4 ± 0.5 Ab	0.2 ± 0.1 Ca	0.2 ± 0.1 Cb	0.7 ± 0.4 BCb	0.9 ± 0.3 Ba
Shrub, 1-hr	10.8 ± 1.4 Ab	2.2 ± 0.2 cc	6.9 ± 0.4 Ba	6.8 ± 0.7 Bb	6.5 ± 0.7 Bb
Shrub, 10-hr	3.1 ± 0.4 Ab	0 ± 0 Cb	0.5 ± 0.4 BCa	0.7 ± 0.2 Bb	1.0 ± 0.2 Bb
Thinning					
Grass	0 ± 0 Ba	1.0 ± 0.4 Aa	1.0 ± 0.5 Aa	0.8 ± 0.4 Aa	0 ± 0 Ba
Litter, 1-hr	16.7 ± 1.7 Ab	3.0 ± 1.0 Cb	5.2 ± 1.8 CB	9.0 ± 1.8 Bc	10.6 ± 1.2 Ba
Litter, 10-hr	7.5 ± 0.8 Aa	0.2 ± 0.2 Ca	0.4 ± 0.2 Cb	0.6 ± 0.9 BCb	0.9 ± 0.3 Ba
Shrub, 1-hr	16.5 ± 2.1 Aa	4.6 ± 0.6 Cb	5.5 ± 0.3 Cb	9.1 ± 1.2 Ba	11.2 ± 1.2 Ba
Shrub, 10-hr	4.9 ± 0.5 Aa	0 ± 0 Db	0.4 ± 0.3 Da	1.6 ± 0.2 Ca	2.9 ± 0.3 Ba
Thinning/herbicide					
Grass	–[d]			2.9 ± 1.3 a	–
Litter, 1-hr				11.2 ± 0.8 b	
Litter, 10-hr				1.6 ± 0.4 a	
Shrub, 1-hr				2.9 ± 1.4 c	
Shrub, 10-hr				0.1 ± 0.1 c	–

[a] Untreated stands have gone at least 10 years without any disturbance.
[b] Means followed by different uppercase letters are significantly different within that treatment and fuel type/size ($\alpha = 0.05$).
[c] Means followed by different lowercase letters are significantly different within that year and fuel type/size ($\alpha = 0.05$).
[d] No data collected for this treatment at this time.

weather conditions lowered this estimate by about 25%.

Flame length outputs from the simulations were similar to estimates derived from existing fireline intensity prediction tables (Hough and Albini, 1978), indicating that they are probably reasonable approximations for these fuel and weather conditions.

3.3. Rate of spread predictions

Rate of spread estimations mirrored predictions of flame length in the years following the thinning and prescribed fire treatments (Fig. 3). In untreated stands under drought conditions, BEHAVE predicted that a bead fire would move at >18 m/min when pushed by a 11.3 km/h wind. The thinning and prescribed fire techniques reduced the rate of spread to 6.7 and 2.3 m/min, respectively, in the first year following treatment. In the years after the thinning treatment, rate of spread rapidly increased and nearly equaled that of the untreated stands by the fifth year. In the prescribed fire treatment, rate of spread also increased as the rough matured, but not as rapidly as in the thinning stands. Simulations for normal weather conditions reduced rate of spread estimates by 45–60%.

Rate of spread estimates in the herbicide treatment for drought conditions were initially high (15 m/min) and increased slightly the first year after treatment to 18 m/min (Fig. 3). From that point, rate of spread dropped rapidly to 3.3 m/min at age 2, 0.7 m/min at age 3 and 1.7 m/min at age 5. Normal weather conditions reduced all rate of spread estimates by

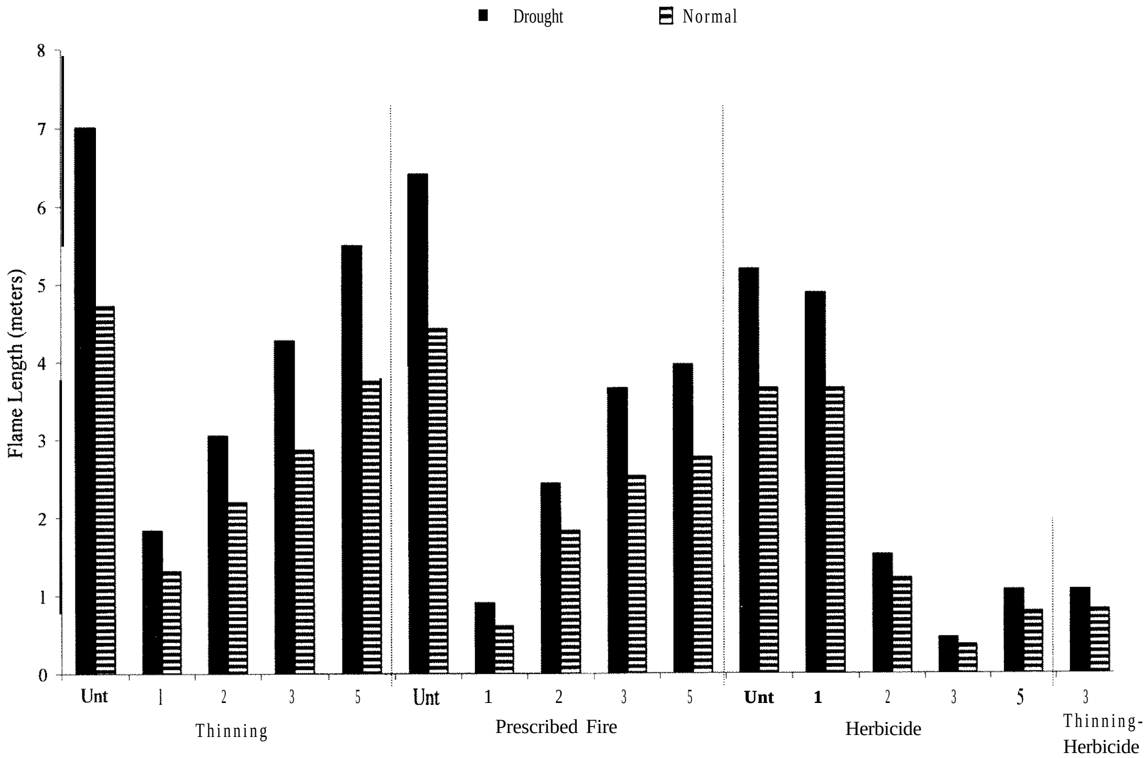

Fig. 2. Wildfire flame length predictions in untreated pine flatwood stands and in stands influenced by fuel reduction technique (herbicide prescribed fire, thinning, or thinning-herbicide), time in years (1, 2, 3 and 5) since last application of the practice and weather conditions.

another 45–60%. Again, the thinning-herbicide treatment produced rate of spread estimates that mirrored those of the herbicide treatment at age 5.

Rate of spread outputs from the simulations were similar to estimates derived from existing fireline intensity prediction tables (Hough and Albini, 1978), indicating that they are probably reasonable approximations for these fuel and weather conditions.

3.4. Difficulty of control predictions

Although fire behavior estimates for normal weather conditions were 40–60% less than those of drought conditions, suppression difficulty of a wildfire was unchanged for each treatment/age-of-rough combination so normal and drought weather estimates were pooled to ease reporting (Fig. 4). In all untreated stands and 1-year-old herbicide stands, a wildfire would probably display extreme fire behavior, i.e. torching, crowning and spotting, making suppression extremely difficult. Conversely, fire behavior in the 1 -year-old prescribe-burned and thinned stands would be mild, allowing for easy control. Difficulty of wildfire control in these two treatments would increase through time as the rough matured. Additional thinning and burning would reduce the rough,, again making control of a wildfire easy and the cycle would repeat itself. Difficulty of wildfire suppression in the herbicide treatment would decrease with time and after the second year would become quite easy and would likely remain that way until harvested for pulpwood. Fire control in the thin-herbicide treatment would be like that of the herbicide-only treatment at age 5.

4. Discussion

In pine flatwood forests, the age and development of the rough determines fire behavior more than any other

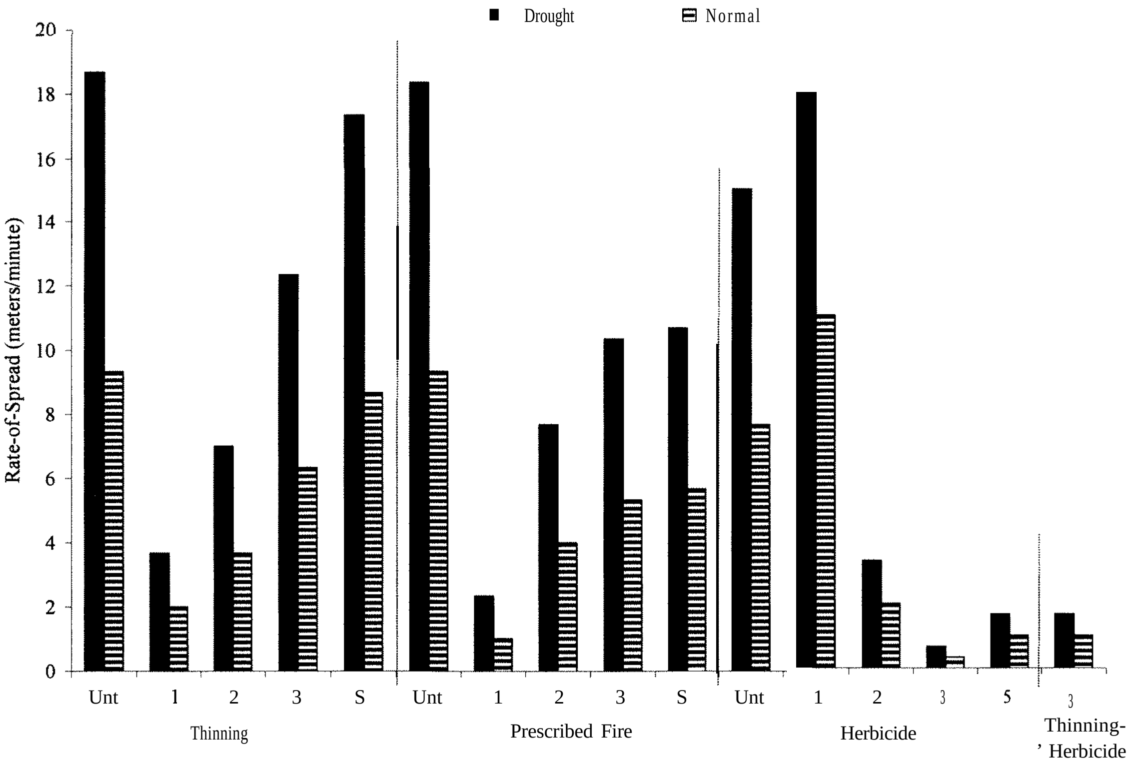

Fig. 3. Wildfire rate of spread predictions in untreated pine flatwood stands and in stands influenced by fuel reduction technique (herbicide, prescribed fire, thinning, or thinning-herbicide), time in years (1, 2, 3, and 5) since last application of the practice, and weather conditions.

forest characteristic (Hough and Albini, 1978). In the untreated stands of this study, the rough was nearly impenetrable, consisting almost completely of highly flammable gallberry and saw palmetto that ranged from 1 to 4 m tall. A summer wildfire in such a setting regardless of whether the conditions are normal or dry, would be extremely dangerous, difficult to suppress and would probably be deadly to all overstory pines. Any of the three fuel reduction treatments in this study would reduce hazardous fuels, but each has its own strengths and weaknesses.

For immediate protection from a stand-replacing wildfire, prescribed fire is the best choice because it creates a fuelbed and structure that cannot support a conflagration. Under the normal or drought conditions simulated, a wildfire in a recently burned (rough age ≤ 1 year) stand would have flame lengths <1 m long and rates-of-spread between 1 and 2 m/min, allowing for direct suppression with relative ease and safety (Fig. 4). Compared to untreated stands, initial pine mortality would be greatly reduced under drought conditions (Outcalt and Wade, 2000) and minimal under normal conditions. However, trees stressed by drought and/or fire can attract bark beetles, i.e. *Dendroctonus frontalis* and a subsequent insect infestation may greatly increase pine mortality.

Thinning (whole tree removal) is the next best immediate approach for protecting against catastrophic wildfire because it disrupts the continuity of the rough and reduces rough height. Such sites allow relatively easy and safe direct attack (Fig. 4) with firefighting equipment and the wildfire would probably kill few of the remaining overstory trees.

Unfortunately, the fire protection provided by a thinning or a prescribed fire is relatively short-lived because gallberry and saw palmetto are well adapted to disturbance, readily sprouting following topkill. As fuels rapidly redevelop, the likelihood of dangerous fire behavior quickly increases. Under the simulated drought weather conditions, flame lengths

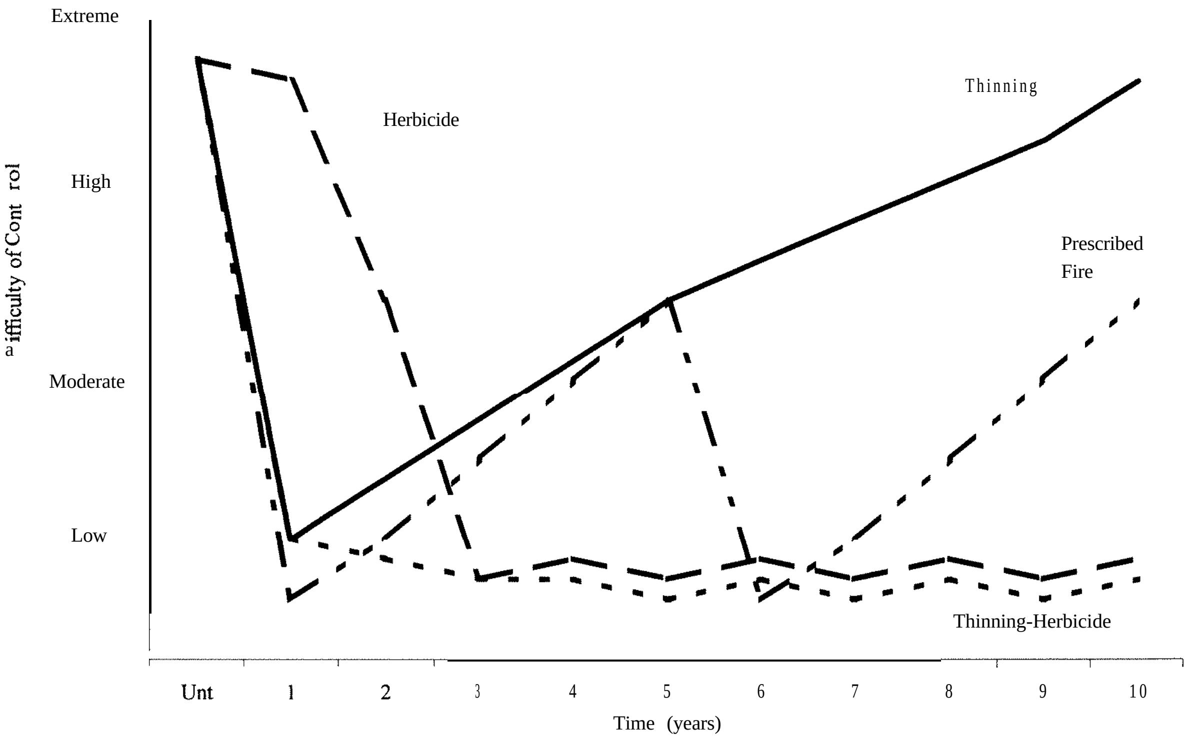

Fig. 4. Probable degree of fire suppression difficulty (low, moderate, high, and extreme) in pine flatwood forests managed with different fuel reduction techniques at various times since last application of the treatment.

in 2-year-old rough were estimated at 3.0 m for the thinning and 2.4 m for the prescribed fire treatments. Such fire behavior would allow direct attack by tractor plows but would be substantially more difficult to control than the l-year-old rough (Fig. 4). By age 5, flame lengths increased to 5.5 m for thinning and 4.0 m for prescribed fire. The resulting threat of crowning, spotting and rapid runs makes fire control more difficult and often necessitates the use of indirect line construction and natural barriers.

Pine flatwood ecosystems evolved with a frequent 2–5year fire cycle (Frost, 1993). Fire provides various benefits (some general and some unique) to this forest type, one being hazardous fuel reduction that protects against stand-replacing wildfires. However, rapid redevelopment of the rough and the necessity of repeating treatments pose a major disadvantage to prescribed fire as a fuel reduction technique. The frequent use of prescribed fire is becoming constrained by shrinking budgets, smoke management, liability concerns and negative perceptions about fire's role in the environment among urban dwellers (Wade, 1993).

Thinnings are plagued with this same rapid rough redevelopment problem. However, commercial entries are usually limited to every 15–20 years (Fig. 4), meaning an extended period of heightened fire danger between treatments unless mitigated by other silvicultural treatments in the interim.

Herbicide application takes the opposite approach to reducing fire behavior. For the first year after treatment, fuel characteristics changed little. The shrubs were dead but still standing, densely spaced and retaining fallen needles (Fig. 1, Tables 4 and 5). On these stands, BEHAVE predicted that a wildfire under drought conditions would have a 5 m flame length and 18 m/min rate of spread and a 4 m flame length and 10 m/min rate of spread under normal weather conditions (Figs. 2 and 3). Difficulty of control would be high to extreme (Fig. 4) and suppression strategy would be the same as an unmanaged stand, indirect attack and natural barriers. Pine mortality from a wildfire in such a scenario would undoubtedly approach 100%.

However, fire danger and control difficulties decrease dramatically beginning in year 2 (Fig. 4) when the treatment consists of saw palmetto eradication followed by a complete herbicide spraying. With this treatment shrub fuels almost disappear, the only 1 h fuel is the blanket of pine needles above the developing duff layer and stands become quite open beginning in the second year. These favorable conditions continue through the sixth year and quite possibly until final harvest if the stand is being managed for pulpwood. Fires would be much less intense than in recently herbicided stands direct attack would be relatively safe and easy.

Unfortunately, the decrease in fire intensity may not translate into a decrease in pine mortality. Herbicide-treated stands will have more duff on the forest floor than stands that are regularly prescribe-burned. Within 3 to 4 years, roots of overstory pines colonize the bottom of the developing duff layer that would be consumed by a drought-year fire. Consequently, a low-intensity fire in an herbicide-treated stand is likely to root-kill more pines than a higher-intensity fire in a stand that is managed with recurrent prescribed fire. Southern pines are adapted to survive crown scorch approaching 95% (Weise et al., 1990; Wade, unpublished data) but are very susceptible to mortality when fire damages their roots (Outcalt and Wade, 2000).

Combining treatments may be a way of capturing the strengths of the different practices and avoiding some of their weaknesses. One example is the thinning-herbicide combination in this study. About 3 years after the last treatment, the stands were quite open with a minimal amount of shrub fuel. Under drought and normal weather conditions, flame length and rate of spread would be low (Figs. 2 and 3) and fire suppression would be relatively easy (Fig. 4). By combining techniques, we suggest that a forest would be immune to catastrophic wildfire, but not to root damage, from treatment application to harvest for pulpwood. This treatment combination warrants more study.

Using fire with herbicides also warrants research The initial prescribed fire would reduce the height of the rough, making a follow-up herbicide application easier, less expensive and more effective. The ecological benefits of fire, preparing seed beds for herbaceous and woody vegetation, promoting germination of plants needing heat scarification of seeds, hastening nutrient cycling and helping control some disease and insect pests, would also be realized (Landers et al., 1995; Pyne et al., 1996). Although, herbicides offer few of these ecological benefits they do provide long-term control of woody shrubs and hardwood sprouts, helping to keep forest environments open for a longer period of time than by prescribed burning alone. This approach may be useful when managing for the suite of endangered wildlife species whose survival depends on open pine forests (Brennan et al., 1998). One caveat pertaining to the initial fire is when a thick forest floor layer exists, a small prescription window is mandatory to minimize duff consumption and attendant tree root mortality.

We advise caution in interpreting the results of this study. Because the experimental design did not account for site quality or past stand history, inherent differences among sites may have confounded the results. For example, the rough redeveloped much quicker in the thinning treatment than it did in the prescribed fire treatment. The cause of this difference may be attributed to treatment differences, site quality, past stand history, or combinations of these factors. Also, the rough-age 5 category consisted of understories ranging from 4 to 6 years old, further adding to the differences in fuel characteristics between those two treatments.

Another limitation to keep in mind is BEHAVE which only predicts average fire behavior at the flaming front of a head fire for a given set of environmental parameters. In this study, we used fuel and weather conditions that we considered typical for early summer in northern Florida and consistent with a near worse-case scenario. Changing location on the fire (flanks or rear) or one or more of the parameters, wind speed, fuel moisture, or relative humidity, would alter the outputs. Far from predicting absolute values, the BEHAVE outputs are only valuable as a relative comparison among treatments. Validation of BEHAVE-generated fire predictions to actual fire behavior for these custom fuel models is still needed for the gallberry-saw palmetto fuel complex, especially under drought conditions. Likewise, comparison of actual fire behavior to BEHAVE-generated estimates for the applicable standard fuel models under drought conditions is another topic awaiting research.

5. Conclusions

Fire has long been a component of Florida's pine flatwood ecosystems and will undoubtedly continue to be as long as lightning is prevalent and population growth challenges traditional fuel reduction techniques. Because of excellent growing conditions, the rough quickly becomes a hazardous fuel problem that when combined with ignition sources and dry weather can produce extreme fire episodes, such as the 1998 season.

Active fuels management is essential to reduce both the size and intensity of wildfires. A passive do-nothing approach will result in catastrophic wildfires and will exacerbate damage and control difficulties. For immediate fuel reduction, prescribed fire is the best technique. However, this technique requires reapplication at 3-5 year intervals to maintain tolerable levels of hazardous fuels. Where the resource management objectives can focus solely on sustaining pine ecosystems, the use of prescription fire should be widespread and frequent with emphasis on breaking up large expanses of heavy fuels. The resulting mosaic of burned stands with roughs of varying ages will increase the success of suppression efforts.

On sites where recurrent fire is not a viable option, thinning offers some of the same fuel reduction benefits. However, time between harvests is usually too long to prevent the rough from developing into the fuel for catastrophic wildfire under a variety of weather conditions.

Herbicide application can be an alternative to prescribed fire and thinning. A single treatment reduces the rough for a longer period but does not provide immediate fire protection or many other fire benefits, such as duff reduction, beat scarification of seeds, nutrient cycling, that are needed to maintain the health of pine flatwood ecosystems.

Combining treatments may be the best approach to managing hazardous fuels and maintaining ecosystem health because the strengths of one treatment can offset the weaknesses of the other. This aspect of fuels management needs more research.

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